The Effect of Bracket Base Pylon Orientation on the Shear Bond Strength of the ODP ANCHOR-LOCK™ Bracket Pad.

A THESIS

Presented to the Faculty of the

Air Force Postgraduate School of Dentistry

Of the Uniformed Services University of the Health Sciences

In Partial Fulfillment of the Requirements

For the Degree of MASTER OF SCIENCE

In Oral Biology

By

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San Antonio, Texas

December 22, 2012

Uniformed Services University of the Health Sciences

Manuscript/Presentation Approval or Clearance

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5. Type of clearance: X Paper __Article __Book __Poster __Presentation __Other

6. Title: 'The Effect of Bracket Base Pylon Orientation on the Shear Bond Strength of the ODP ANCHOR-LOCK™ Bracket Pad'

7. Intended publication/meeting: June 2013

8. "Required by" date: 1 July 2013

9. Date of submission for USU approval: 6 June 2013

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6. DoD clearance/date:

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DEDICATION

This thesis and research is dedicated to my family for their patience, understanding and love.

ACKNOWLDEGMENTS

First and foremost I would like to thank Dr. Brent Callegari for his guidance, mentorship, and encouragement to complete this project. Next I would like to thank Dr. Kraig Vandewalle for his help with statistical analysis and direction using the necessary research equipment. Thank you ODP for providing bracket specifications, images and fabrication information. Finally, I would like to thank Mr. Miller and staff for manufacturing the stainless steel bracket jig used in this study.

ABSTRACT

Introduction: The purpose of this study was to compare the shear bond strength of three different pylon orientations on the ODP ANCHOR-LOCK™ bracket pad.

Null hypothesis: Pylon orientation does not significantly affect shear bond strength.

Methods: Three groups, consisting of 25 brackets each, were bonded to secured surfaces of Transbond XT. Each group of brackets had a distinct pylon orientation. The three different pylon orientations included: Group 1 (0 degree brackets with 90 degree pylons), Group 2 (-7 degree brackets, with acute pylon orientation to shear force), and Group 3 (-7 degree bracket flipped to achieve +7 degree bracket with obtuse pylon orientation to shear force). Shear bond strength was determined using a universal testing machine. An analysis of variance, one-way ANOVA test was performed to determine if there was a significant difference between the three different pylon orientations. A Tukey HSD test was used to help determine which orientations were significantly different from one another. The Kruskal Wallis test was used to assess the Adhesive Remnant Index (ARI) scores for any significant differences. After a difference was determined, the Mann-Whitney test was used to determine which groups were significantly different ($P < 0.05$).

Results: No significant differences existed between Groups 1 and 2. Group 3 was found to have significantly lower shear bond strength than groups 1 and 2 ($P < 0.001$). Group 3 was also found to have a significantly lower adhesive remnant score (less adhesive remaining on the bracket) than groups 1 and 2 ($P < 0.001$).

Conclusions: This study concluded that pylon orientation affects shear bond strength. Perpendicular and acute of pylon angles (relative to the direction of force applied) had significantly higher shear bonds strengths (and more adhesive remnants within the bracket base) than obtuse pylon angles. However, no significant differences were found between perpendicular and acute pylon orientations in regards to: shear bond strength, and ARI (Adhesive Remnant Index).

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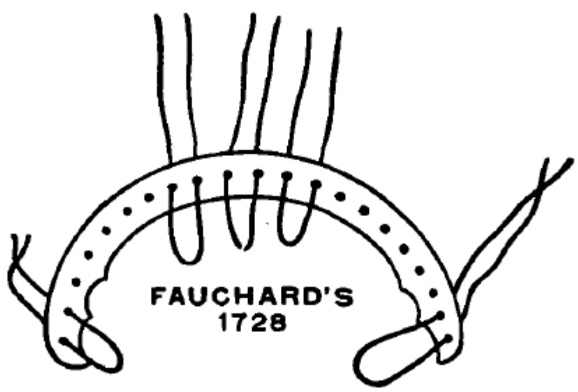
I. BACKGROUND AND LITERATURE REVIEW

A. INTRODUCTION

1. Orthodontics before Brackets

Humans have attempted to improve tooth alignment for a very long time. According to the American Association of Orthodontists, in “no later than 1,000 B.C., ancient Greeks began using base metals and cat gut in a determined effort to take the smile provided by nature and make it better.” The first scientific attempt at tooth alignment occurred in 1728, when Pierre Fauchard constructed the bandeau (Brodie, 1934). The bandeau was made from a flat metal strip connected to the teeth by pieces of thread which allowed the dentition to be tipped into an expanded arch form (Figure 1). Delabarre published the plan of the wire crib in 1826, marking the birth of contemporary orthodontics (Figure 2). “Delabarre’s wire crib was used for the purpose of keeping the antagonizing teeth apart while other teeth were being regulated by strings. This crib probably suggested to later operators the use of cribs for anchoring metallic springs” (Farrar, 1888). In 1841, Schange invented the first bands which consisted of metal strips with screws to adjust the size. The first dental cement for securing bands to teeth was developed in 1870 by Magill (Steiner, 1933). According to Steiner (1933), Edward Angle invented edgewise brackets attached to bands in 1928 (Figure 3). Early 20th century orthodontic appliances were primarily made from precious metal, steel, and vulcanite. It took until the late 1950s for stainless steel to be widely accepted as a suitable material for arch-wires and other appliances (Sellke, 1999).

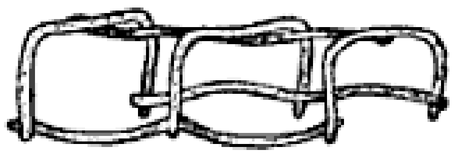
Figure 1: Fauchard's Bandeau. Although Fauchard appears to be one of the earliest writers who described mechanisms for correcting irregular teeth, he does not claim that the strip was originated by him. M. Desirabode, a later writer (1823), in speaking of these strips, says that he thinks they have probably been in use since "ancient times" (Farrar, 1888).



(Steiner, 1933)

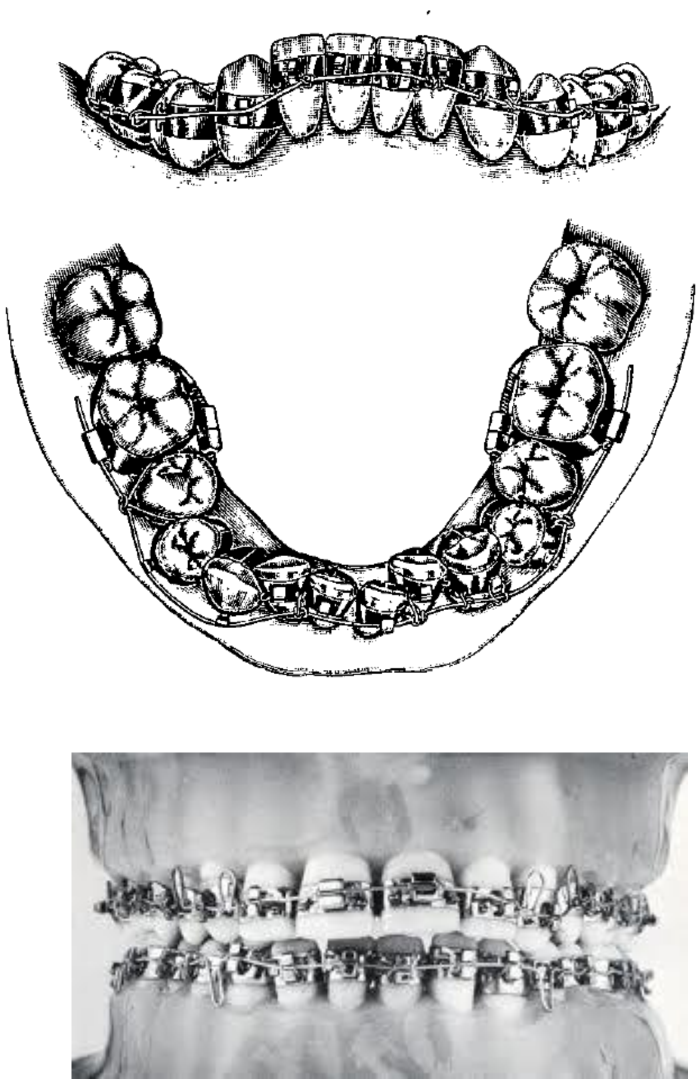
Figure 2: Delabarre's Crib

A - This was made of six pieces of wire bent and soldered together as shown (Farrar, 1888).



B - When ready to apply it was forced over the side teeth as shown below, the lower wires hugging tightly their necks (Farrar, 1888).

Figure 3: Edward Angle's Edgewise appliance. Band designed to allow relatively efficient control of tip, torque and rotation (Steiner, 1933).



2. The Shift from Bands to Brackets

The orthodontic community has been bonding brackets directly to enamel since the development of three critical techniques: Buonocore's introduction of enamel etching in 1955 (Buonocore, 1955), the development of composite resin cements (Bowen, 1962) and Newman's description of how to bond attachments directly to enamel using epoxy resin in 1965 (Newman, 1965). Direct bonding of orthodontic brackets has advantages over banding that have made its use widespread for nearly half a century. These improvements include: esthetics, ease of manipulation, decreased patient discomfort, decreased gingival irritation, improved oral hygiene maintenance, control over partially erupted teeth and the elimination of band thickness (Reynolds, 1975; Bishara et al, 1999). To create a successful bond, three factors are vital: (1) the tooth surface, (2) the adhesive, and (3) the bracket backing (Reynolds, 1975).

3. Tooth Surface and its Preparation for Bonding

Fully formed enamel is a highly mineralized extracellular matrix, consisting of 96% mineral and 4% organic matrix and water. The inorganic content of enamel is mainly crystalline calcium phosphate, called hydroxyapatite (Ten Cate, 1994). Untreated enamel does not contain enough porosity to allow for clinically sufficient bond strength (Cehreli et al, 2006).

In an effort to increase the adhesion to the tooth surface, Buonocore (1955) pioneered the acid-etching technique with 85 percent phosphoric acid. The irregular

enamel surface (microporosities) created by dissolving hydroxyapatite crystals permits penetration of the fluid-adhesive components of the bonding system and this penetration provides micromechanical retention (Basaran et al, 2007; Retief, 1978). It is now known that phosphoric acid concentrations greater than 50 percent result in the formation of a monocalcium phosphate monohydrate that inhibits further dissolution and concentrations above 10% does not significantly decrease bond strength (Chow et al, 1973; Gottlieb et al, 1982). Currently, phosphoric acid concentrations between 30-40% are used (Silverstone, 1974). Specifically, 37% phosphoric acid is most commonly used clinically as it provides similar bond strengths to higher concentrations, with less damage occurring to the enamel surface (Denys and Retief, 1982; Sadowsky et al., 1990; Carstensen, 1992). With 37% phosphoric acid, 15 seconds of etching is sufficient (Carstensen, 1986; Osario et al, 1999).

Self-etching primers have become popular in an effort to improve the efficiency of the bonding procedure. The suggested benefits of self-etching primers include: maintaining clinically useful bond strengths while minimizing the amount of enamel loss, and simplifying the technique by reducing the number of steps (Cal-Neto et al, 2006). Several studies have found that self-etching primers are able to achieve clinically acceptable levels of bond strength and there is not a statistically significant difference between conventional multi-step etch and prime and self-etching techniques (Bishara et al, 2001; Arnold et al, 2002, Velo et al, 2002;

Cacciafesta et al, 2003; Dorminey et al, 2003; Ireland et al, 2003; Larmour et al, 2003; Cehreli et al, 2005; e Cal-Neto et al, 2006).

4. Adhesives

a. Development

Development of the direct bonding technique was closely related to the advances in adhesives that were capable of withstanding the forces needed for orthodontic treatment and could be removed when then treatment was complete. In 1962, Bowen developed the BIS-GMA formula on which current orthodontic bracket bonding is primarily accomplished. Newman (1965) began with an epoxy resin, but found that the 15-minute cure time was too long and switched to modified acrylic resins with a cure time of five minutes. The advances in adhesives have continued. A 2003 Cochrane Summary (Mandall et al, 2009) compared a chemically cured composite, with light-cured composite, conventional glass-ionomer cement and polyacid-modified resin composite (compomer). The results of this summary were inconclusive. However, Faltermeier et al (2007) noted that the best mechanical properties could be achieved by incorporating high concentrations of filler particles of various sizes into the resin. When Vilchis et al (2008) compared five orthodontic adhesives (Transbond XT, Light Bond, BeautyOrtho Bond, Kurasper F, Heliosit Orthodontic, and a flowable orthodontic resin Salivatect), it was determined that there is no superiority of any specific filler because every type of filler offers advantages and disadvantages.

b. Resin-Based Composites

Composite materials consist of two or more components. A resin-based composite typically contains three major components: an organic binder, inorganic filler and a coupling agent (Craig, 1977; Phillips 1982). The organic resin matrix is the chemically active component.

The least ideal characteristic of resin-based composites is volumetric shrinkage during the conversion of monomer to polymer (Combe et al, 2000). The resin matrix of all resin-based composites undergoes volumetric shrinkage of approximately 10%. This shrinking causes stress at the bonded interface with the adjacent tooth surface (Glen, 1982). The total polymerization shrinkage of comparable chemically-activated and light-activated resins do not differ significantly (Phillips, 1991; Craig, 1997). Fillers reduce the polymerization shrinkage and coefficient of thermal expansion of the material as well as improve abrasion resistance (Craig 1997). Resin-based composites can be classified according to particle filler size:

- Mega-fill 0.5–2 millimeters
- Macro-fill 10–100 microns
- Mid-fill 1–10 microns
- Mini-fill 0.1–1 microns
- Micro-fill 0.01–0.1 microns
- Nano-fill 0.005–0.01 microns

Modern orthodontic resin-based composites are mini-filled, with particles averaging 0.1-1 um. The filler content of orthodontic resin cements is lower than restorative resins. This is primarily for the properties of sufficient bond strength and easier removal of the remaining cement during debonding (Smith & Williams, 1982).

c. Glass Ionomer Cements (GICs)

In orthodontics, Type I GICs are typically used. They are usually used for cementing bands, but they have also been used to bond orthodontic brackets. Type II GICs are restorative materials, and Type III are lining materials and fissure sealants (Richardson, 2010).

Fluoride is an important component of a GIC as it assists in the manufacturing of the glass by lowering fusion temperature and enhances the working characteristics and mechanical properties of the cement (Wilson & Nicholson, 1993). Glass ionomer cements also have the ability to release (Fox, 1990; Ashcraft et al., 1997) and absorb fluoride (Hatibovic-Kofman & Koch, 1991; Creanor et al., 1994). Studies comparing fixed appliance treatment bonded with either glass ionomer or composite adhesive found that there was a significant reduction in the number of white spot lesions only when total treatment time exceeded 16-18 months (Marcusson et al., 1993; Millett et al., 1999).

Glass ionomer cements adhere directly to enamel without the need for additional bonding agents and surface treatments (Millet and McCabe, 1996). The primary mechanism for adhesion is derived from the ability of the acid to clean,

penetrate and roughen the tooth surface which decreases surface energy and facilitates both micromechanical and chemical bonding (McClean, 1996).

d. Resin-modified Glass Ionomer Cements (RMGIC)

These cements combine the advantages of conventional GICs with the mechanical and physical properties of composite resin cements (Beress et al., 1998). Resin-modified glass ionomer cements undergo both a polymerization reaction (involving the resin monomer) and a significant acid-base reaction (large enough to produce a settling reaction in the dark) (Bourke et al., 1992; McClean et al., 1994). Resin-modified glass ionomer cements that possess photochemical settling reactions also appear to have a reduction in sensitivity to moisture, since the resin network reduces the diffusion of external water into the settling cement (Cho et al., 1995; Shen and Grimaudo, 1994).

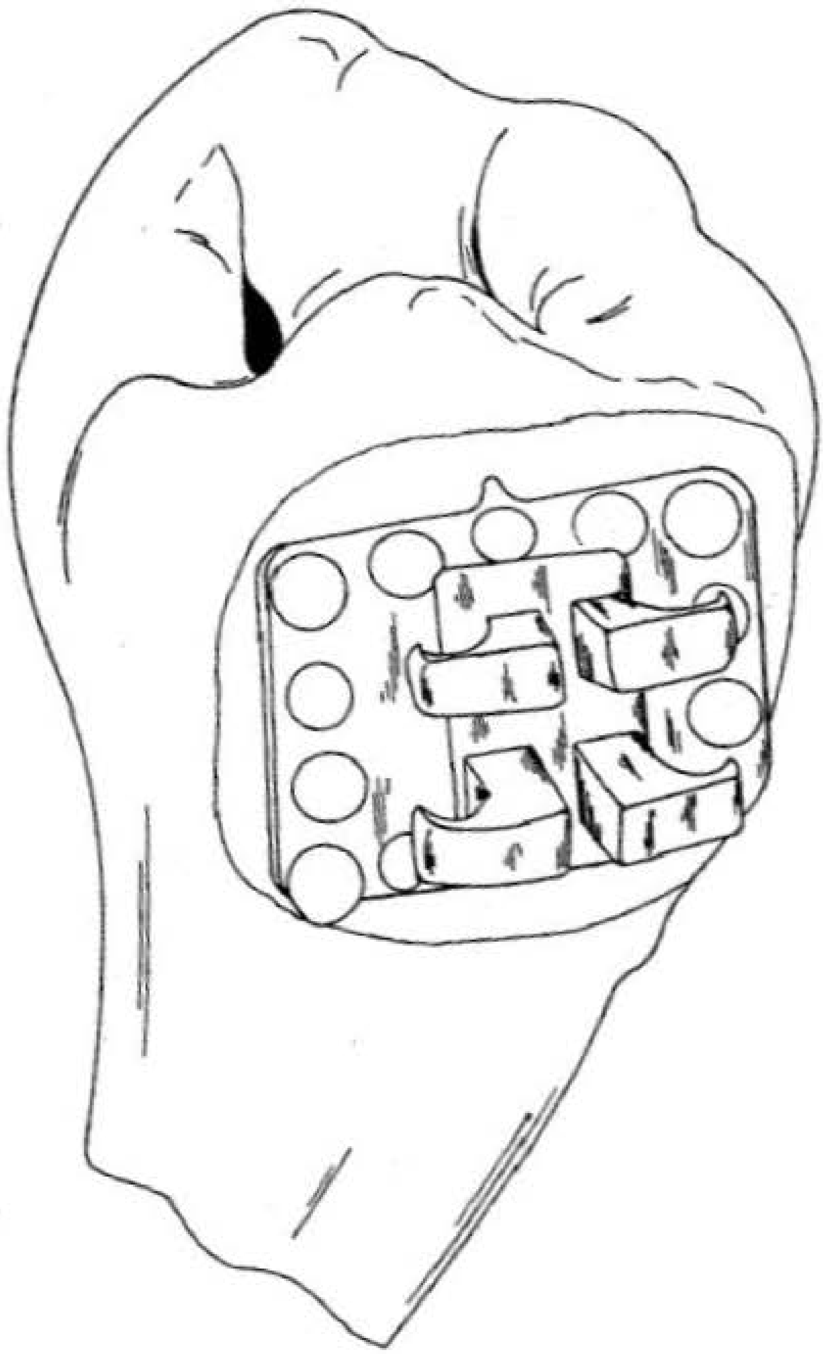
5. Bracket Base

a. Metal

When using metal brackets, most bonding failures occur between the cement and the bracket (Algera et al, 2008; Knoll et al, 1986; Wang et al, 2004). This holds true when brackets are debonded (Hanson et al, 1983, Simoka et al, 1985). One explanation for this finding may be that metal bracket bases rely on mechanical retention (Lombardi et al, 2007) since they do not form a chemical bond with the adhesive (Furguson et al., 1984).

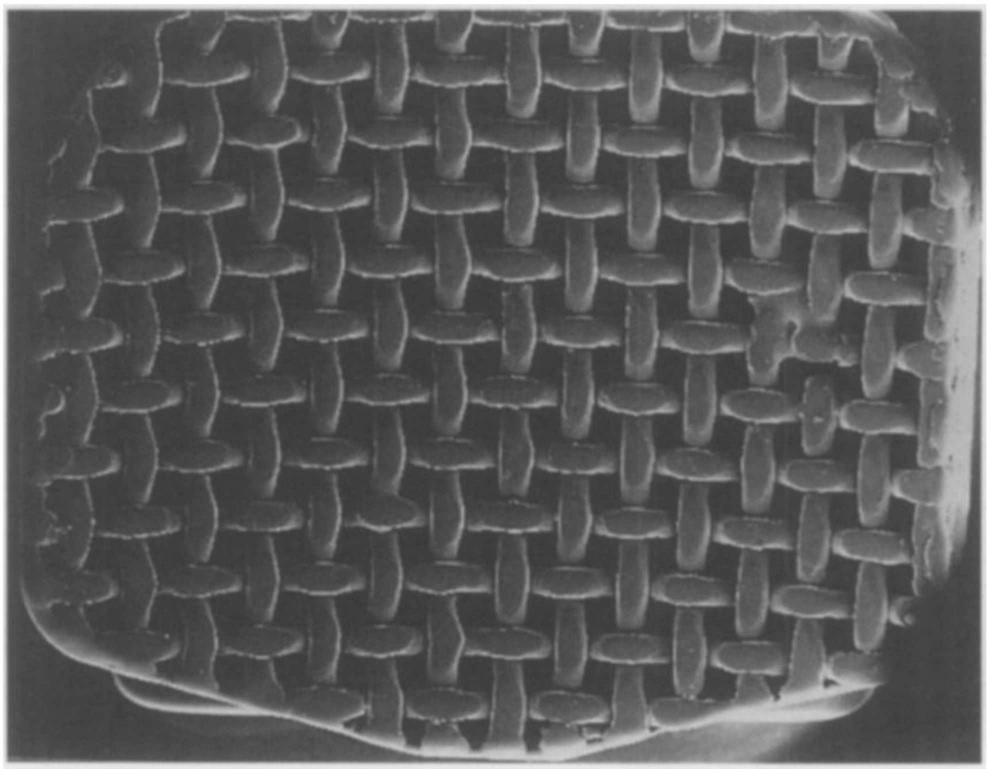
The initial metal bracket bases were milled from cold-drawn stainless steel and had crude perforated bases (Figure 4) into which adhesive could flow (Sheykholeslam and Brandt, 1977, Thanos et al., 1979). This original base design is no longer used due mainly to: limited mechanical bond strength, plaque retention, and poor esthetics. In an attempt to improve these properties, many types of base surfaces have been developed. One of the first design improvements was the introduction of foil-mesh bracket bases (Figure 5), which resulted in greater bond strength (Reynolds and von Fraunhofer, 1977; Faust et al., 1978, Thanos et al., 1979; Lopez, 1980). This new base design was also shown to have a smoother, less plaque-retentive surface (Maijer and Smith, 1981). In the initial design, the foil mesh was welded to the bracket base. It was later suggested that these weld points lead to stress concentrations in the adjacent resin, decreasing the base bond strength (Dickson et al, 1980; Maijer and Smith, 1981). The solution for this was found by using a laser for welding or mesh attachment by brazing yielding better tensile and shear bond strengths (Dickinson and Powers, 1980; Lopez, 1980; Maijar and Smith, 1981).

Figure 4: Perforated bracket base.



(Waller DE, 1974)

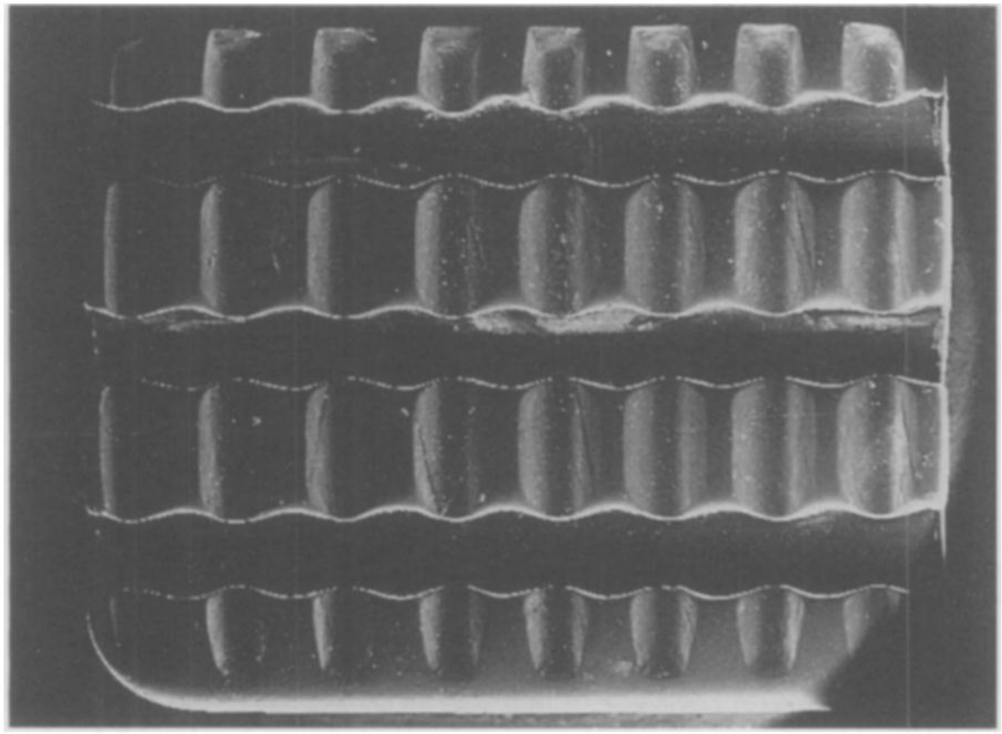
Figure 5: Foil mesh base.



(Willems et al, 1997)

Another bracket innovation is the integral base bracket (Figure 6). In this design the bracket and base are cast as an integral unit and incorporate undercut channels for mechanical retention (Mahal, 2000). This type of bracket can be machined (milled) or cast. Of the two designs, cast appears to have greater micro-mechanical retention resulting in higher bond strengths (Regan & van Noort, 1989).

Figure 6: Cast integral base.



(Willems et al, 1997)

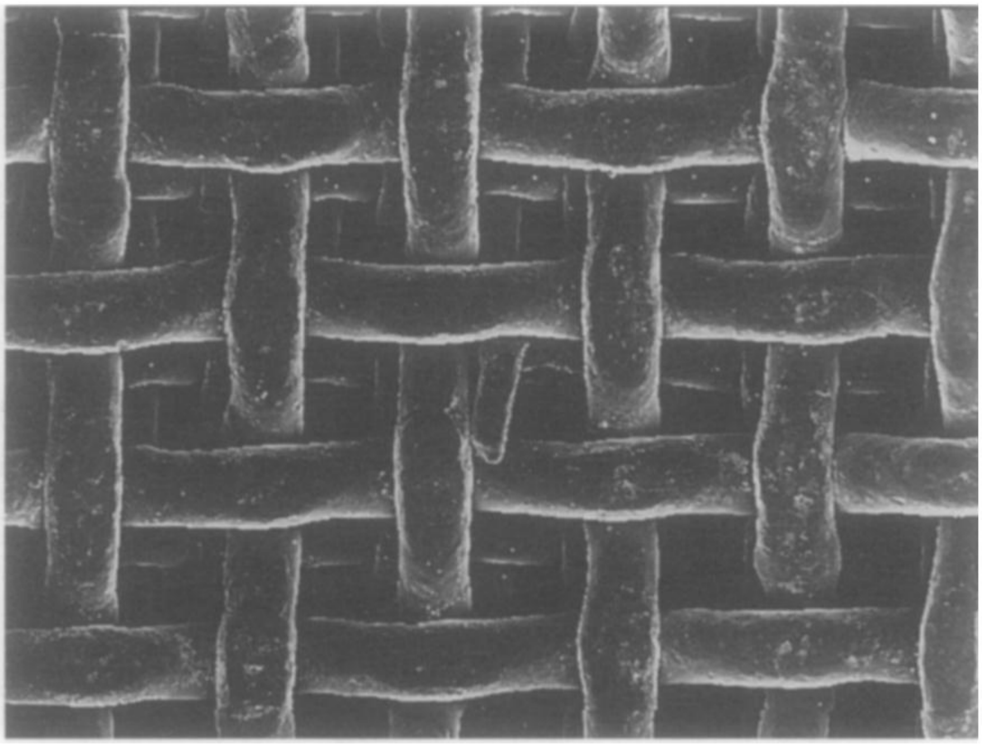
When the different base types are compared, they yield somewhat conflicting results. 80 gauge mesh foil has been found to be the most retentive mesh foil size, providing for large spaces for the penetration of the adhesive and the curing light (Maijer et al, 1981, Sharma-Sayal et al, 2003). However, it has also been found that no significant differences were found between 80 gauge mesh, 100 gauge mesh, and mini and standard-size bases (Cucu et al, 2002). Cast integral bases have shown superior bond strengths when compared with a conventional foil mesh and an integral milled base (Regan & van Noort, 1989). However, mesh-based brackets have been found to be more retentive in tension, whereas metal-based brackets were more retentive in shear (Thanos et al, 1979). Fine-mesh base had higher tensile bond strength than coarse mesh, and both had a higher tensile strength than the undercut base (Smith et al, 1991). Victory Series brackets have shown superior bond strength to the majority of integral base brackets (Cozza et al, 2006). Although no overall trend has been identified to this point, it appears that certain combinations of bracket base and bonding agent perform optimally (Knox et al, 2000; Urabe et al, 1999).

Regan and van Noort (1989) suggested that the adhesive/bracket interface strength may be improved by improving the base design to increase the amount of available undercut while allowing for the escape of air and excess adhesive. In addition, maximum advantage can be taken of the undercut areas if they have a roughened surface to provide additional micromechanical retention. Since light does not travel through metal bracket bases, it has been suggested that polymerization of

a light-cured adhesive resin may be incomplete (Sargison et al., 1995). Knox et al (2000) added that particular base designs may allow improved adhesive penetration or improved penetration of the curing light.

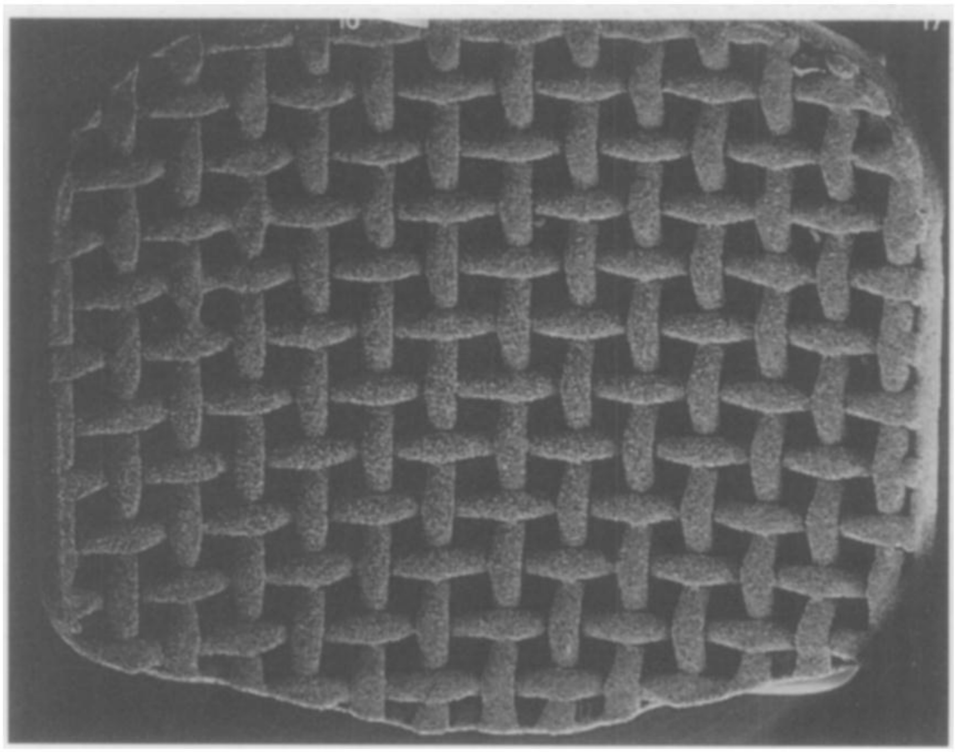
In an effort to further increase micromechanical retention, multiple techniques have been investigated. Examples include: additional photo-etch techniques (laser structuration, electroerosion), double-mesh/super mesh (Figure 7) (Lombardi et al, 2007), sandblasting (Figure 8), etching, surface activation, sintering, and adhesive precoating. Even the surface area of the base has been examined. MacColl (1995) has shown that if a bracket base has a surface area of less than 6.82 mm^2, shear bond strength is significantly decreased.

Figure 7: Super Mesh/Double mesh base.



(Willems et al, 1997)

Figure 8: Sandblasted mesh base.



(Willems et al, 1997)

b. Ceramic

In response to demands for better aesthetics during treatment, ceramic brackets (Figure 9) were introduced in the 1980s (Birnie, 1980; Russell, 2005). Early ceramic brackets used a silane-coupling agent to act as a chemical mediator between the ceramic bracket base and the adhesive resins. This chemical bond resulted in extremely high bond strengths. The combination of the ceramic's high resistance to deformation and the extremely high bond strengths results in enough stress to the enamel during debond to risk enamel damage (Russell, 2005; Forsberg & Hagberg, 1992). Additionally, as the ceramic and cement interface bond strength increases, the incidence of bond failure occurring at the enamel-cement interface increases. Bond failure in this location results in an increased incidence of enamel fractures (Swartz, 1988b; AAO 1989, Harris et al, 1990; Joseph and Rossouw, 1990; Storm, 1990; Machen, 1990). Due to this, the majority of ceramic brackets currently rely solely on mechanical retention. When debonding mechanically retained ceramic brackets the risk of enamel damage is no greater than metal brackets (Habibi et al. 2007)

Figure 9: Ceramic base.

(Willems et al, 1997)

Ceramic brackets have other properties to consider. Machined ceramic brackets produce significantly greater frictional forces than stainless steel brackets (Omana et al. 1992). The brittleness of ceramic brackets can cause problems at debond (Gibbs, 1992). The opposing dentition can incur significant enamel wear if in contact with ceramic brackets (Douglas, 1989).

6. Lighting

Tavas and Watts first described the use of visible light to cure the composite resins used to bond orthodontic appliances to enamel in 1979. Light-cured composites have multiple advantages over chemically cured: ease of use, extended working time, improved brackets placement, easier cleanup, and faster cure of the composite (Jonke et al., 2008). Curing light as well as ambient light can affect the ultimate shear bond strength of orthodontic adhesives. Light-cured adhesives are polymerized by a reaction between the catalyst in the adhesive and the photons emitted by the light source (Gange, 2006).

Light-curing units have evolved from heavy, bulky, corded units with halogen lamps to lightweight, portable, light-emitting diode (LED) units. The greatest advantages in light-curing technology have been made with the curing lights, rather than the composites themselves (Gange, 2006). The amount of time required to cure the adhesive depends on the manufacturer's recommendation and the wavelength emitted by the curing light.

7. Clinical Bond Strength Requirements

Accidental bracket debonds continue to cost orthodontists in both treatment time and money. Graber et al (2005) have reported that the median rate of bond failure for practitioners in the United States is around 5%. Reynolds (1975) and Whitlock el al (1994) have reported that a minimum bond strength of 4.9-7.1 MPa is required for successful orthodontic treatment. However, 20-25 MPa can lead to damage of the enamel upon debond due to excessive bond strength (Cal-Neto et al 2006, Yamada et al 2002). An investigation by Retief, (1974) indicated that enamel fractures can occur on debonding with bond strengths as low as 9.7 MPa. Creating the desired location of bond failure and titration of bond strength is a challenging process. If the bond between the cement and the enamel is stronger than the enamel itself, the enamel will fracture during debonding. For example, the use of silane coupling agents on ceramic bases enhances the bond of the luting cement to the ceramic bracket base to the point that it competes with the cohesive strength of enamel (Odegaard, 1989; Storm, 1990). The resulting enhanced bond strength between the ceramic bases and the cement results in bond failure at the enamel-cement interface instead of the cement-base interface (Storm, 1990). These factors both contribute to the likelihood of enamel fracture during debonding.

8. Bond Failures and ARI

Bond failure location plays an important role when it comes to chair time and potential damage to the enamel surface (Katona, 1997). Bond failures can be divided into two types: cohesive failure and adhesive failure. Cohesive failures occur within the tooth, the bracket, or the cement. Adhesive failure occurs at the tooth-

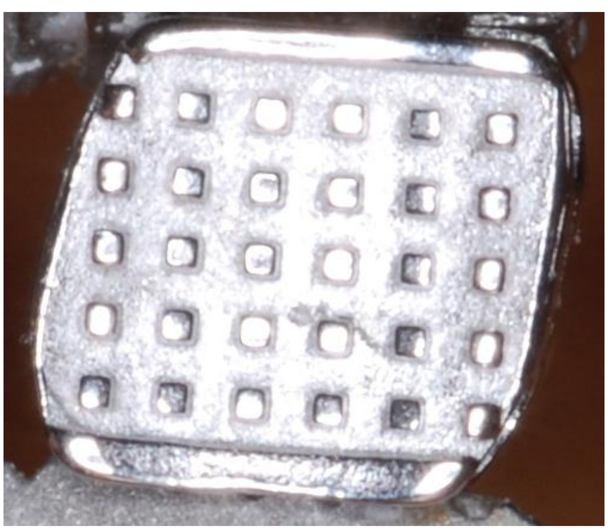
cement and the bracket base-cement interfaces (Compton et al., 1992; Wang and Meng, 1992). The enamel-cement interface is an undesirable bond failure location due to the increased risk of damage to the enamel. In order to protect the enamel surface, the ideal bond failure location when debonding is between the bracket base and the cement (Sinha et al. 1995).

Most bonding failures occur between the cement and the bracket (Algera et al, 2008; Knoll et al, 1986; Wang et al, 2004). The Adhesive Remnant Index (ARI) was formulated by Artun and Bergland (1984) and is used to quantify the amount of cement left on the tooth following debonding of the bracket. The ARI score can be used to identify the sites of bond failure between the enamel, the cement and the bracket base. The traditional ARI scoring system consists of a 4-point scale of 0-3. A score of 0 indicates no cement is left on the tooth, 1 indicates less than half of the cement is left on the tooth, 2 indicates more than half of the cement is left on the tooth, and 3 indicates that all of the cement is left on the tooth including a distinct impression of the bracket base.

To test the shear bond strength of different pylon orientations, 75 of ODP's (Orthodontic Design and Production) ANCHOR-LOCK™ PAD based brackets were used (Figure 10). ODP claims, "The ANCHOR-LOCK™ PAD utilizes pylons instead of the traditional mesh mechanical retention system. ANCHOR-LOCK™ bases are designed with an EDM (Electrical Discharge Machining) finish on all five pylon surfaces to maximize bracket retention, and the pylons are engineered at an acute

angle relative to the torque, generating geometric undercuts when bonded” (ODP Website, 2012).

Figure 10: ODP's Comfort Zone™ Series with Anchor-Lock™ Pad.



(Anchor-Lock™ Pad)

Geometrically, an acute pylon angle should provide the greatest mechanical retention and therefore the highest bond strength. However, Knox et al (2001) found that acute cement-enamel angles resulted in an increased chance of singularity development and attachment failure (i.e., the stress points created by these acute angles could lead to failure). This study examines the effect of acute, perpendicular, and obtuse pylon orientation on shear bond strength.

II. OBJECTIVES

A. Purpose of the Present Study

The purpose of this *in vitro* study is to determine if retention pylon orientation affects shear bond strength of orthodontic brackets.

B. Specific Hypothesis

An acute pylon orientation (from the facial to the occlusal surface) will have significantly higher shear bond strength than an obtuse pylon orientation.

C. Null Hypothesis

Pylon orientation does not significantly affect shear bond strength.

III. MATERIAL AND METHODS

A. Experimental Design

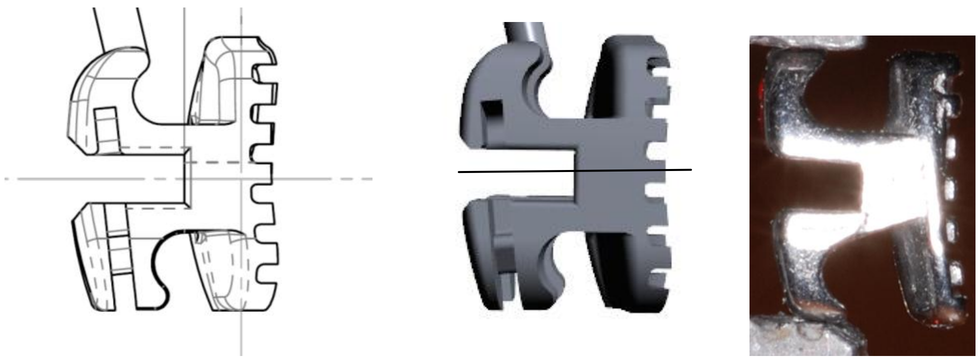
ODP ANCHOR-LOCK™ bracket pad's manufacturing process requires that the bracket slot is parallel to the pylons. For this reason, the maxillary canine MBT bracket prescription was selected in order to allow for multiple pylon orientations (-7, 0, and +7 degrees), while minimizing differences in bracket specifications. 75 brackets were separated into three groups of 25. The three groups were divided according to their pylon orientation and were labeled: Group 1 (0 degree brackets with 90 degree/perpendicular pylons), Group 2 (-7 degree brackets, with acute pylons to shear force), and Group 3 (-7 degree bracket flipped 180 degrees to achieve +7 degree bracket with an obtuse pylon to shear force) (Figure 11).

To ensure the bond failures took place at the adhesive-base interface, the brackets were bonded to a solid Transbond XT™ surface. This surface was created using a stainless-steel bracket jig (40mm high with a 58mm diameter). Undercuts were added to the bonding sites to firmly secure the composite into the cylinder. Transbond XT™ was pressed into the cylinder's undercuts and formed to the contoured surface with a mylar strip. The Transbond XT™ was then light cured with a VALO™ (ULTRADENT, SOUTH JORDAN, UT) curing light at a constant distance and angle for 10 seconds from the occlusal and 10 seconds from the gingival. The curing light was tested prior using a resin calibrator (BlueLight™ analytics, HALIFAX, NOVA SCOTIA, CANADA) to ensure adequate and consistent curing. The reading for the VALO™ (ULTRADENT, SOUTH JORDAN, UT) curing light was 1300

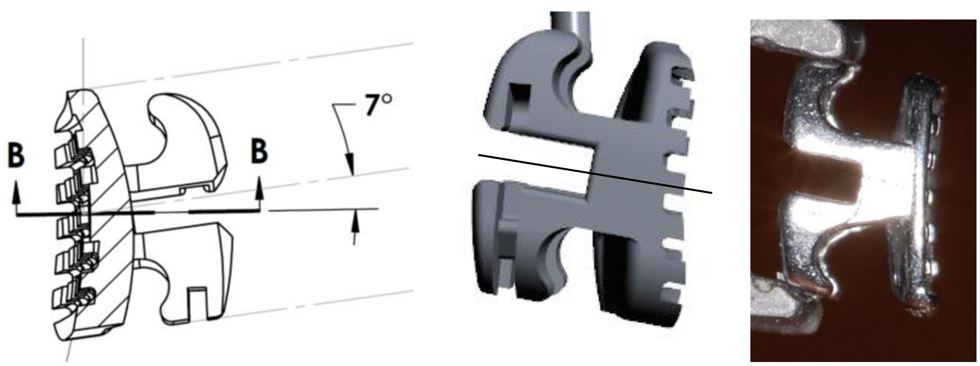
mW/cm2. The Transbond XT™ surface was then micro-etched since trials demonstrated a weak point at the solid adhesive surface and bracket base adhesive without this step. Immediately after, Transbond XT™ was pressed/buttered onto the bracket base and the bracket base was pressed onto the jig's Transbond XT™ surface. The technique used a height gage and the same provider for consistent bracket placement. The excess composite material was removed with an explorer. The seated bracket was then light cured at a constant distance and angle for 10 seconds from the gingival and 10 seconds from the occlusal (Figure 12).

Figure 11: Pylon Orientation Groups

A - Group 1: 0 degree bracket



B - Group 2: -7 degree bracket



C - Group 3: +7 degrees (achieved by flipping -7 degree bracket)

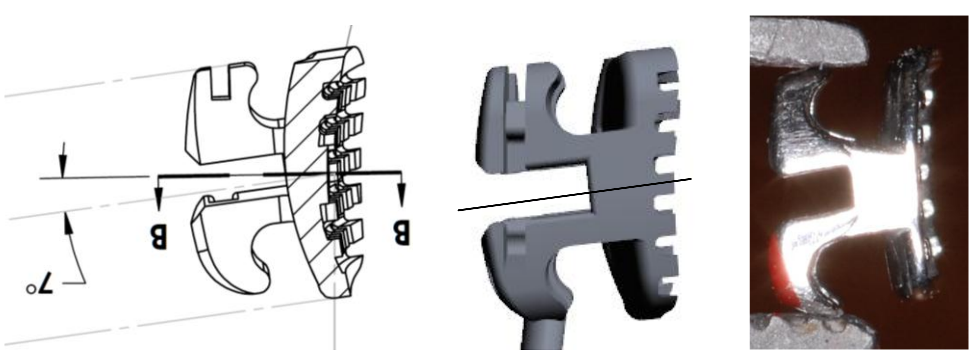
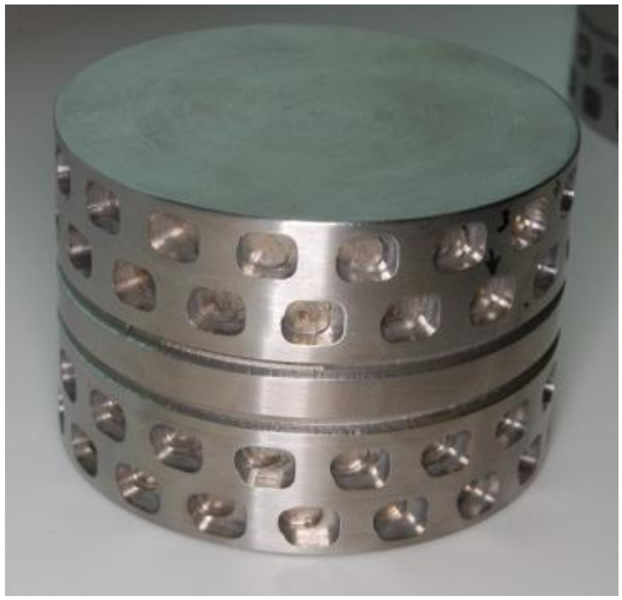


Figure 12: Specimen Preparation

A - Stainless-steel bracket jig (40mm high with a 58mm diameter).



B - Transbond XT^{TM} was pressed into the cylinder's undercuts.

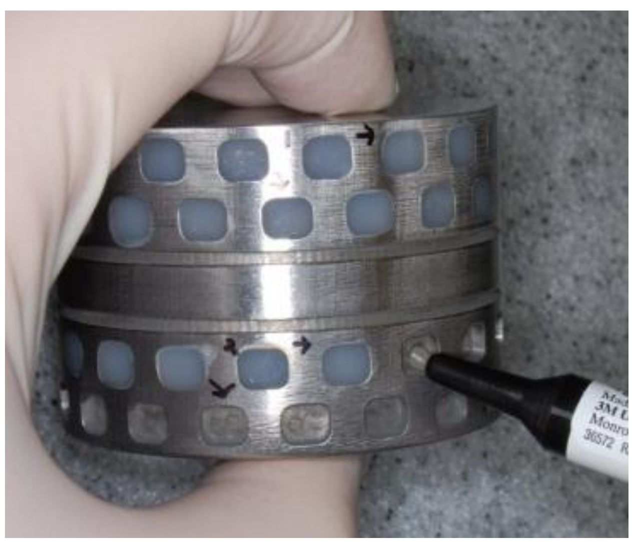


Figure 12: Specimen Preparation (Continued)

C - Formed to the contoured surface with a mylar strip and light cured with the VALO™ (ULTRADENT, SOUTH JORDAN, UT) curing light at a constant distance and angle for 10 seconds from the occlusal and 10 seconds from the gingival direction.

D - Transbond XT™ was pressed/buttered onto the bracket base.

Figure 12: Specimen Preparation (Continued)

E - The bracket base was pressed onto the jig's Transbond XT^{TM} surface. The technique used a height gage and the same provider for consistent bracket placement.

F - The seated bracket was then light cured at a constant distance and angle for 10 seconds from the gingival and 10 seconds from the occlusal.

The samples were loaded into a universal testing machine (Instron® Corp, Model 5543, Canton, MA), and a straight blade using a crosshead speed of 1.0mm/min descended upon the bracket until bonding failure occurred (Figure 13). Shear bond values in Megapascals (MPa) were calculated from the peak load of failure (in Newtons) divided by the specimen surface area (0 deg brackets= 18.7666 mm^2, +/-7 deg brackets = 18.8928 mm^2) provided by the bracket manufacturer in square inches. This was converted to square millimeters in order to complete the Megapascal calculations. The 0 degree bracket base area is 0.02908835 square inches= 18.7666 square millimeters. The -7 degree bracket base area is 0.02928405 square inches= 18.8928 square millimeters (Table 1 and Figure 14). The mean and standard deviation were determined for each group.

Figure 13: Instron® Universal Testing Machine Shear Force

A - The samples were loaded into a universal testing machine (Instron® Corp, Model 5543, Canton, MA).

B - A straight blade using a crosshead speed of 1.0mm/min descended upon the bracket until bonding failure occurred.

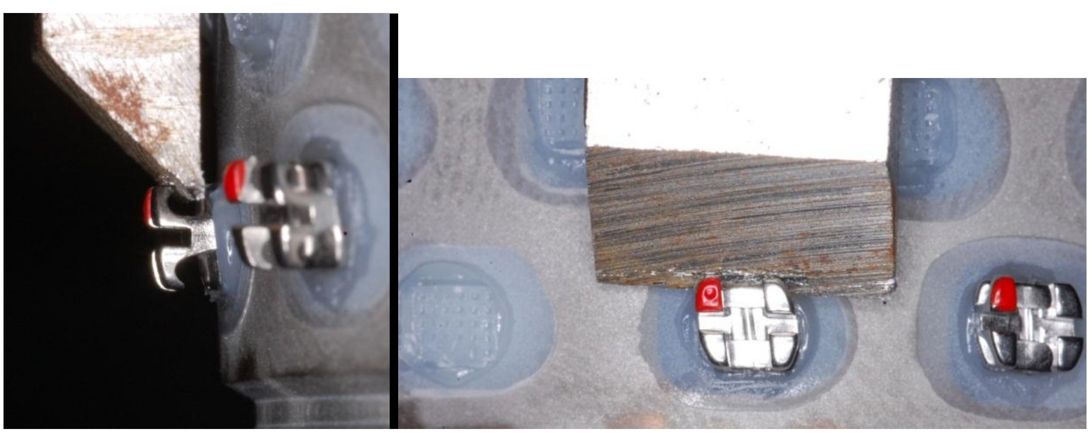


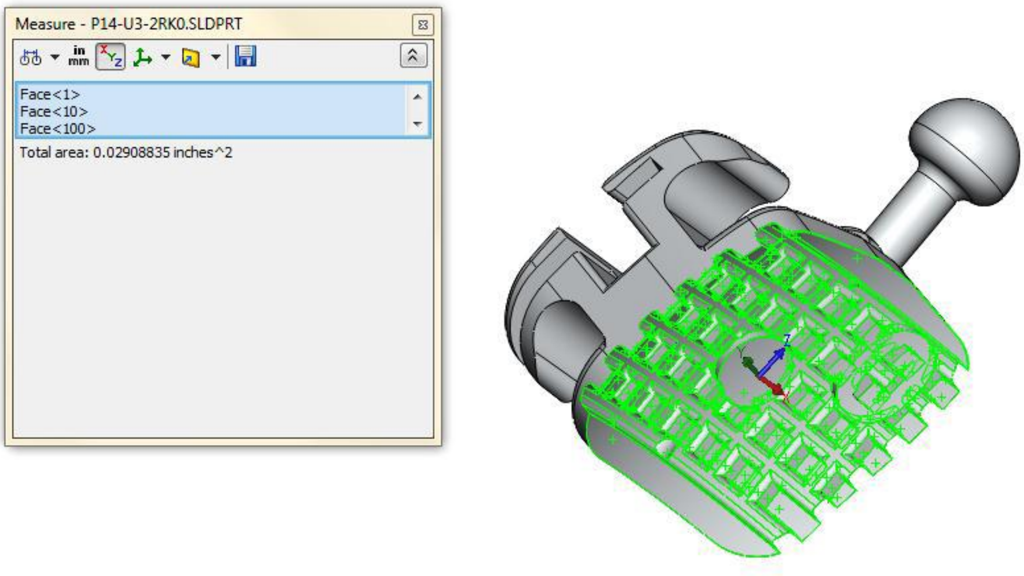
Table 1: Bracket Base Surface Area

Convert square inches to square millimeters.

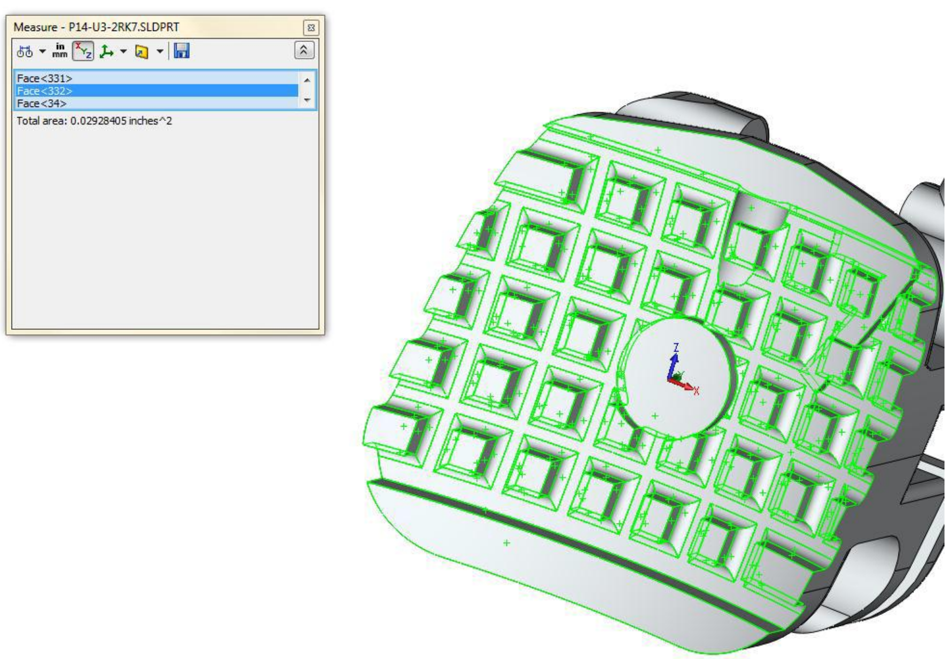
Bracket Base S.A.	mm^2	In^2
Group 1 (0 degree bracket)	18.7666	0.02908835
Group 2 (-7 degree bracket)	18.8928	0.02928405
Group 3 (+7 degree bracket)	18.8928	0.02928405

Figure 14: Bracket Base Surface Area

A - Zero degree bracket



B - Negative seven degree bracket (Also used as + seven degree bracket)



B. Statistical Management of Data

An analysis of variance, one-way ANOVA test was then performed to determine if there was a significant difference between the three different pylon orientations. The established alpha factor was 0.05, meaning that a p-value less than 0.05 would result in the rejection of the null hypothesis at the 5% significance level. We then incorporated a Tukey HSD test to help determine which orientations are significantly different from one another accounting for the standard error.

A modified Adhesive Remnant Index (ARI) was used to evaluate the amount of adhesive left on the bracket base after debonding to establish the sites of adhesive fracture. The ARI scoring was done by an individual unassociated with this study to prevent bias in scoring. Brackets were observed with magnification (Nikon SNZ-1B at 10X magnification), and the adhesive remaining was scored with respect to the amount of resin material remaining: ARI 0, no adhesive retained on the bracket base with a clear and distinct impression of the bracket base on the substrate; ARI 1, less than half of the adhesive retained on the bracket base; ARI 2, more than half of the adhesive retained on the bracket base; ARI 3, all of the adhesive retained on the bracket base. See Table 2 and Figure 15.

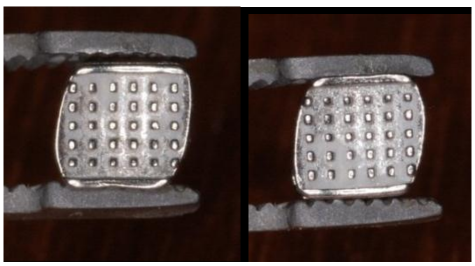
Table 2: ARI Legend

ARI Score	% of Bracket Base Covered by Adhesive
0	0
1	1-50
2	51-99
3	100

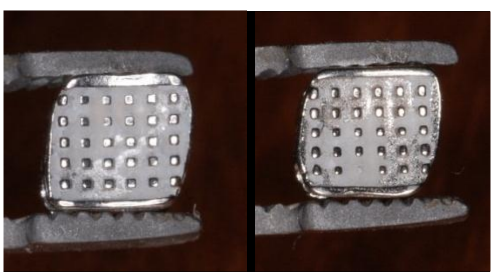
Figure 15: ARI Examples

A - ARI=0: 0% Bracket Base Covered by Adhesive.

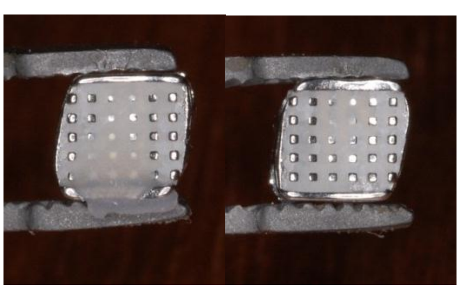
B - ARI=1: 1-50% Bracket Base Covered by Adhesive.



C - ARI=2: 51-99% Bracket Base Covered by Adhesive.



D - ARI=3: 100% Bracket Base Covered by Adhesive.



The Kruskal Wallis test was used to evaluate the ARI. This was done since the Kruskal Wallis test is the nonparametric equivalent of the one-way ANOVA analysis and can be used to determine if there is a significant result in the grouped data. The Mann-Whitney test was then run to help determine which groups ARI were significantly different from each other.

IV. RESULTS

Table 3 shows the average shear bond strength and ARI value for Group 1 (0 degree bracket with 90 degree Pylon orientation): 97.7 N (SD= 18.6), 5.21 MPa (SD= 1), and 2.1 ARI (SD= 0.4). Table 4 shows the average shear bond strength and ARI value for Group 2 (-7 degree bracket with acute Pylon orientation): 99.4 N (SD= 9.8), 5.26 MPa (SD= 0.5), and 2.0 ARI (SD= 0.4). Table 5 shows the average shear bond strength and ARI value for Group 3 (+7 degree bracket with Obtuse Pylon orientation): 79.0 N (SD= 18.7), 4.18 MPa (SD= 1), and 1.1 ARI (SD= 0.3). Table 6 compares the averages of all three groups.

Table 3: Group 1 (0 degree bracket, 90 degree Pylon Orientation) Shear Bond Strength and ARI Values

Bracket Test #	Peak load of failure (N)	MPa= N/(mm^2)	ARI
1	108.511	5.78	2.00
2	51.009	2.72	3.00
3	93.425	4.98	2.00
4	98.878	5.27	2.00
5	129.146	6.88	2.00
6	86.989	4.64	2.00
7	110.617	5.89	2.00
8	96.951	5.17	2.00
9	120.523	6.42	2.00
10	123.718	6.59	2.00
11	102.382	5.46	2.00
12	90.829	4.84	2.00
13	74.055	3.95	3.00
14	118.856	6.33	3.00
15	90.768	4.84	2.00
16	88.819	4.73	2.00
17	126.102	6.72	2.00
18	95.574	5.09	2.00
19	70.858	3.78	2.00
20	91.312	4.87	2.00
21	101.496	5.41	2.00
22	85.359	4.55	1.00
23	77.301	4.12	2.00
24	108.392	5.78	2.00
25	100.854	5.37	2.00
Average	97.709	5.21	2.08
Standard Deviation	18.5604	0.99	0.4

Table 4: Group 2 (-7 degree bracket, Acute Pylon Orientation to shear force) Shear Bond Strength and ARI Values

Bracket Test #	Peak load of failure (N)	MPa= N/(mm^2)	ARI
1	107.887	5.71	2.00
2	93.273	4.94	2.00
3	108.260	5.73	3.00
4	105.541	5.59	2.00
5	111.118	5.88	2.00
6	84.023	4.45	2.00
7	96.795	5.12	2.00
8	99.832	5.28	2.00
9	96.307	5.10	2.00
10	98.135	5.19	2.00
11	87.173	4.61	2.00
12	81.644	4.32	2.00
13	109.656	5.80	2.00
14	101.790	5.39	2.00
15	108.296	5.73	2.00
16	91.684	4.85	2.00
17	88.462	4.68	2.00
18	111.787	5.92	2.00
19	99.825	5.28	2.00
20	109.383	5.79	3.00
21	96.171	5.09	2.00
22	109.946	5.82	2.00
23	109.644	5.80	2.00
24	80.856	4.28	1.00
25	96.412	5.10	2.00
Average	99.356	5.26	2.04
Standard Deviation	9.7559	0.52	0.351188

Table 5: Group 3 (+7 degree bracket- Obtuse Pylon Orientation to shear force) Shear Bond Strength and ARI Values

Bracket Test #	Peak load of failure (N)	MPa= N/(mm^2)	ARI
1	8.307	0.44	1.00
2	81.620	4.32	1.00
3	70.147	3.71	1.00
4	85.714	4.54	1.00
5	96.580	5.11	1.00
6	84.714	4.48	1.00
7	99.631	5.27	2.00
8	101.364	5.37	1.00
9	81.709	4.32	1.00
10	89.450	4.73	1.00
11	81.382	4.31	1.00
12	81.292	4.30	1.00
13	68.512	3.63	1.00
14	58.462	3.09	1.00
15	75.424	3.99	1.00
16	66.985	3.55	1.00
17	70.462	3.73	1.00
18	92.746	4.91	1.00
19	72.014	3.81	1.00
20	71.939	3.81	1.00
21	101.791	5.39	2.00
22	79.016	4.18	2.00
23	80.294	4.25	1.00
24	79.042	4.18	1.00
25	95.623	5.06	1.00
Average	78.969	4.18	1.12
Standard Deviation	18.67447	0.99	0.33166

Table 6: Group Means Compared

Group (N=25)		N (Newtons)		MPa (Megapascals)		ARI (Adhesive Remnant Index)	
Group	Degrees	Mean	St Dev	Mean	St Dev	Mean	St Dev
1	0	97.709	18.5604	5.21	0.99	2.08	0.4
2	-7	99.356	9.7559	5.26	0.52	2.04	0.351188
3	+7	78.969	18.67447	4.18	0.99	1.12	0.33166

Comparing shear bond strengths

The Univariate Analysis of Variance revealed a significant difference among the three groups; $p < 0.001$. The Tukey HSD test revealed which groups were significantly different from each other (Table 7 and Figure 16). Group 3 was found to have significantly lower shear bond strength than groups 1 and 2 ($P < 0.001$). Groups 1 and 2 were not significantly different from each other.

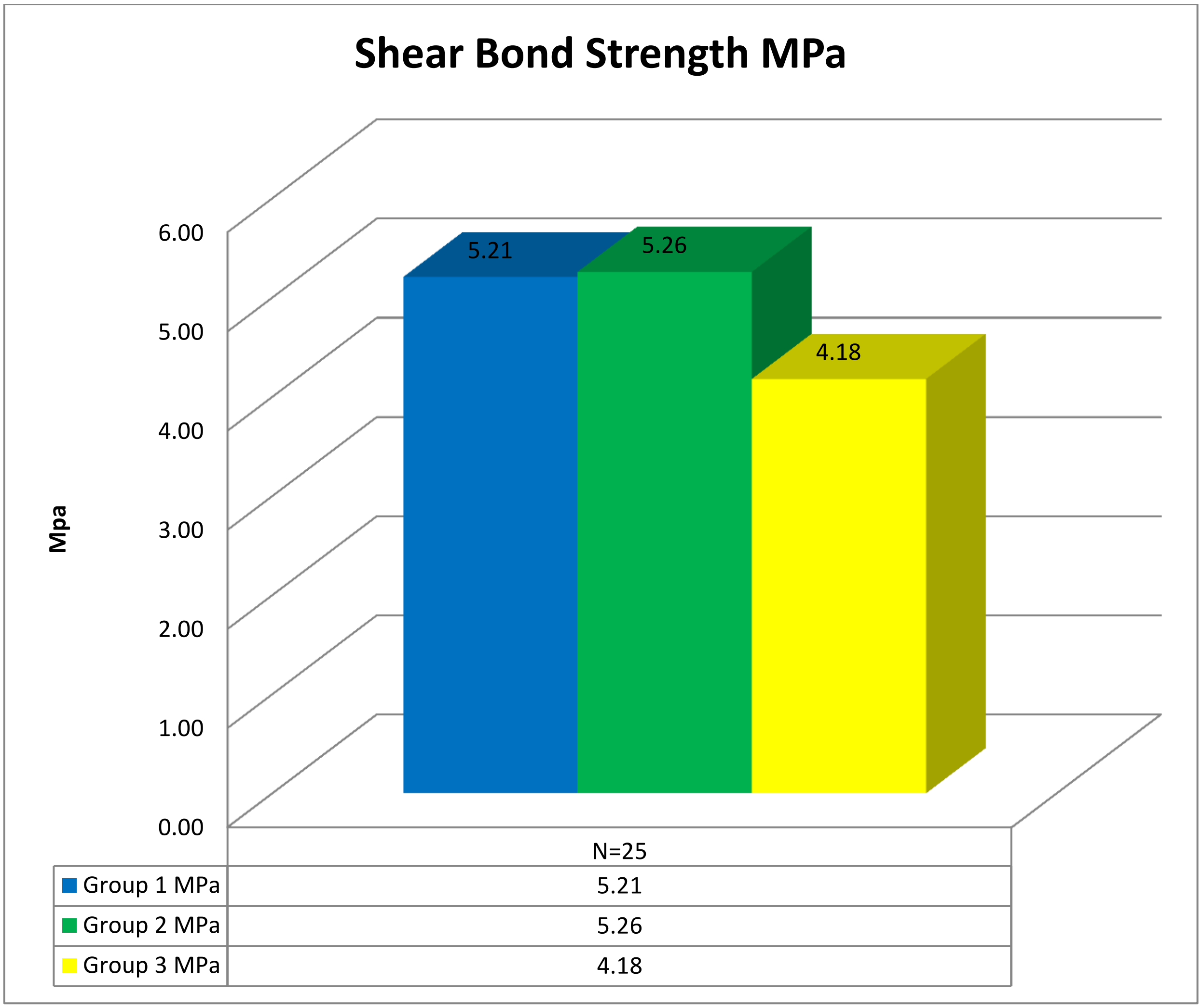
Table 7: Tukey HSD

MPa (Std. Deviation)

Group	a	b
1) 0 deg	5.2072 (0.9875)	
2) -7 deg	5.2580 (0.5165)	
3) +7 deg		4.1792 (0.9849)

Groups under the same letter column are not significantly different (P> 0.05). Group 3 is significantly different from groups 1 and 2 (P <0 .001).

Figure 16: Shear Bond Strength MPa



ARI (Adhesive Remnant Index)

The mean ARI score for each group was: group 1= 2.1, group 2= 2.0, and group 3= 1.1. When comparing the adhesive remnant indexes, the Kruskal-Wallis Test revealed a significant difference exists between the groups ($P < 0.001$). The Mann-Whitney Test revealed that group 3 retained significantly less adhesive in the bracket base (lower adhesive remnant score) than groups 1 and 2. Groups 1 and 2 were not significantly different from each other (Table 8 and Figure 17).

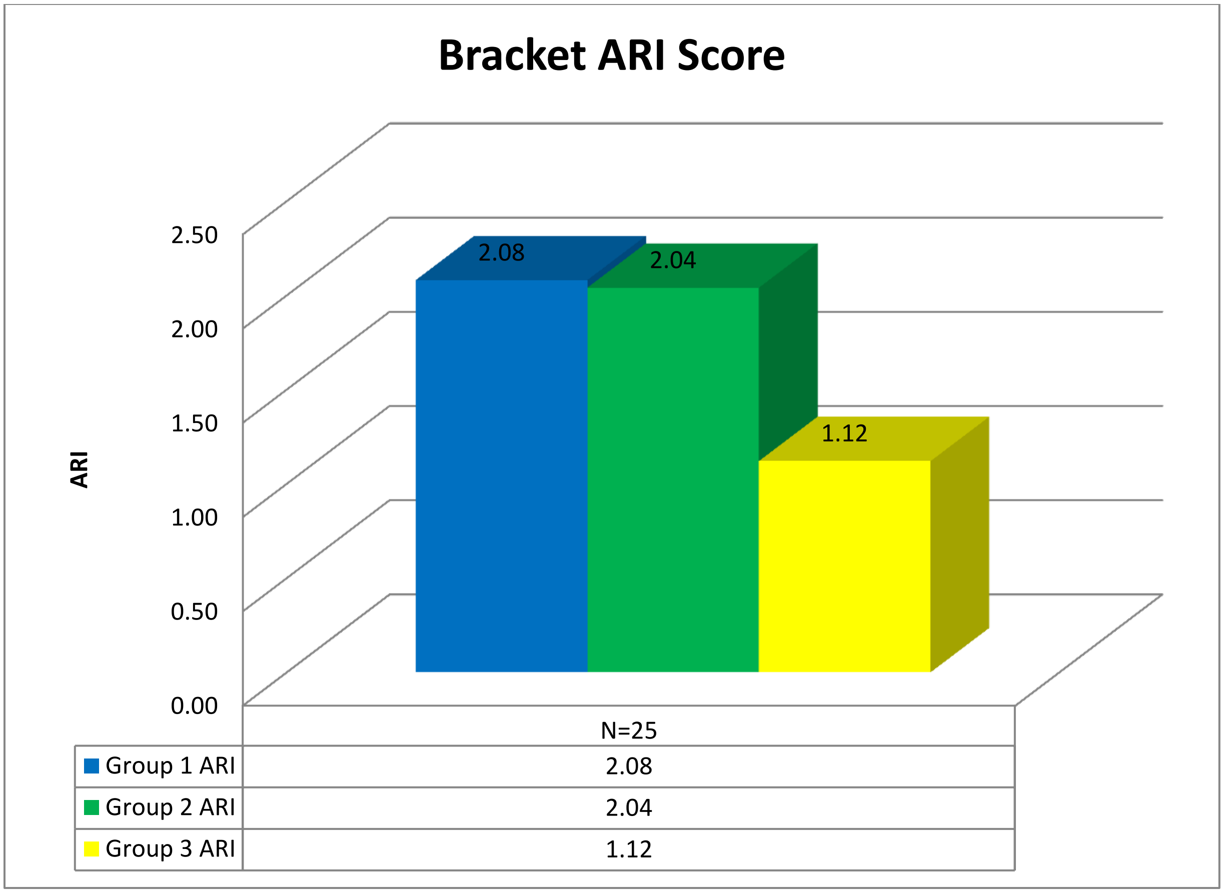
Table 8: Mann-Whitney Test

ARI Average (Std. Deviation)

Group	a	b
1) 0 deg	2.08 (0.4)	
2) -7 deg	2.04 (0.35)	
3) +7 deg		1.12 (0.33)

Groups under the same column letter are not significantly different (P> 0.05). Group 3 is significantly different from groups 1 and 2 (P <0 .001).

Figure 17: Bracket ARI (Adhesive Remnant Index) Score



In summary, the results indicate that a significant difference exists between bracket orientation, shear bond strength and ARI. Group 3 (+7 degree bracket, obtuse pylon orientation) had significantly lower shear bond strength than groups 1 and 2. Group 3 also retained significantly less adhesive on the bracket base.

V. DISCUSSION

Bond strength of orthodontic brackets has been studied for more than thirty years. The key features of bracket bond strength orthodontists have been searching for include: withstanding functional and mechanical forces while remaining bonded to the tooth for the duration of treatment, and at the end of treatment being able to easily remove the bracket without damaging the tooth surface (Richardson, 2010). Even though considerable progress has been made regarding the titration of bond strength and conservation of enamel, accidental debonds remain a source of frustration for both patients and practitioners alike.

Extensive literature exists regarding different types of bracket bases and their affect on shear bond strength; however, this researcher has not discovered any literature that examined the orientation of base pylons and its affect on shear bond strength.

The purpose of this *in vitro* study was to determine if retention pylon orientation affects shear bond strength of orthodontic brackets. 75 of ODP's (Orthodontic Design and Production) ANCHOR-LOCK™ PAD based brackets were used to test this question. The results indicated the 90 degree and acute pylon orientation angles were significantly more resistant to shear forces than an obtuse angle ($P < 0.001$). The 90 degree and acute angles also retained significantly more of the adhesive in the bracket base ($P < 0.001$) as determined by the ARI (Adhesive Remnant Index).

Reynolds (1975) and Whitlock el al (1994) have reported that a minimum bond strength of 4.9-7.1 MPa is required for successful orthodontic treatment. All pylon orientations tested with the exception of the obtuse pylon orientation (+7 degrees) fell within this range. The negative 7 degree bracket averaged 5.26 MPa, the 0 degree bracket averaged 5.21 MPa and the positive 7 degree bracket averaged 4.18 MPa. Overall, these values were somewhat low debond strengths. Especially when considering that more modern shear bond strength studies report desired bond strengths of 8-12 MPa (Bishara et al, 2001; Bishara et al, 2005). However, this experiment focused on the comparison between different pylon orientations (while limiting as many variables as possible) rather than focusing on absolute shear bond strength values. Differences existed between the in vitro model and the clinical application that may significantly change the raw MPa value. Perhaps the most significant difference was the use of a Transbond XT block as a bonding substrate instead of enamel.

Bonding to secured blocks of Transbond XT allowed for consistency and close observation on how the failure took place within the adhesive layer or within the bracket base-cement interface. However, the additional thickness of the Transbond XT may have introduced unknown variables. For example, bonding to a secured block of Transbond XT may have allowed more distortion at the adhesive surface than enamel would have during shear force application.

The shapes and orientation of the brackets were not identical. Minor differences exist between the 0 degree and -7 degree brackets. The +7 degree

bracket was the -7 degree bracket flipped 180 degrees. These differences may also have had an effect on shear bond strength. We did not only vary the pylon orientation and keep other bracket features identical due to the current manufacturing process. The current manufacturing process requires that the pylon orientation is in the same plane as the arch wire slot.

ODP's ANCHOR-LOCK™ PADs are currently designed to create geometric undercuts relative to the torque (ODP Website, 2012). The results of this study suggest that this bracket design is more guarded against debonding from the mechanical forces of torqueing than if the bracket was designed with an obtuse angle relative to the torque. However, a 90 degree angle relative to the torque may offer statistically similar bond strength. It is important to note that the statistical differences may not equate into clinical importance.

In *vivo*, bonded brackets are exposed to dynamic forces. Hammad et al (2012) found survival rates did not show significant differences between the upper and lower dental arches ($P > 0.05$), torquing forces may be the most appropriate force to guard against. However, in 2002, Adolfsson et al did find that bond failure rates have been shown to be significantly higher in the mandible. This suggests that biting forces are worth considering. The average biting force that an individual produces during chewing is 14kg (137N) and the average maximum biting force is 31 Kg (304 N) (Proffit, et al 1983).

An interesting finding was that there was not a significant difference in shear bond strength between 90 degree and acute pylon orientation. Further examination

on the range of pylon orientations is needed, but this suggests that having acutely-angled pylons does not offer increased bond strength in comparison to pylons at a right angle to the substrate surface. There was also no significant difference between ARI (adhesive remnant index) scores between these two groups. This means that the amount of cement left on the substrate surface is similar for both the 90 degree and acute angle groups.

These findings could lead to innovations for bracket removal. The same bracket could have different shear bond strengths depending on the direction of force applied in regards to pylon orientation. Ideally, for maximum retention, the pylons would be oriented in either a 90 degree or at an acute angle relative to the expected forces the bracket will have to endure. In addition, the bracket base would have an obtuse pylon orientation relative to the intentional debond force direction to decrease the force needed. For example, a mandibular bracket could have its acute angle facing occlusally to resist mastication forces and its obtuse angle from the gingiva to decrease the force needed to debond in an occlusal direction. Theoretically this would result in equal greater resistance against accidental debonds and increased ease (i.e. decreased force required to remove bracket) of intentional debonds. While using a debonding force to obtain an obtuse pylon direction would decrease the force required, it would also result more adhesive being left on the tooth surface. This bracket cement interface is the ideal failure site to maintain enamel integrity (Sinha et al, 1995). However, this would lead to increased difficulty of enamel clean-up (Brown, 1978; Pus, 1980). According to Van

Waes (1996), although the average enamel loss that occurs while removing orthodontic adhesive with carbide burs is only 7.4 um, great care must be taken to avoid excessive damage to the enamel surface.

VI. CONCLUSIONS

This study concluded that pylon orientation affects shear bond strength. Significantly higher shear bonds strengths are associated with perpendicular and acute angles of pylons (from the direction of the force applied) in comparison to an obtuse angle. However, at the angles tested (+/- 7 degrees), acute pylon orientation did not significantly increase bond strength in comparison to a 90 degree angle. It is likely that once a certain acute degree is reached, the trend would begin to reverse itself and lead to lower shear bond strengths. Continued research needs to be done to compare the entire range of possible pylon orientations and their associated shear bond strengths. This information could be used to ensure we are achieving the maximum bond strength possible, or conceivably customize brackets to resist different levels of shear bond strength depending on location and forces the bracket is subjected to. Additionally, the potential exists to affect the ease of intentional debonds by varying the pylon orientation and direction of force applied.

This study also found that pylon orientation affects the ARI (adhesive remnant index) score. Higher ARI scores (more cement remaining in the bracket and by inference, less cement remaining on the substrate surface) are associated with a perpendicular and an acute angle of pylons from the direction of force applied. At the angles tested, having an acute angle (- 7 degree bracket) instead of a 90 degree

angle did not significantly increase ARI score. In summary, obtuse pylon orientation to shear force applied results in less cement remaining on the bracket surface (more on the substrate surface) and 90 degree and acute pylons result in more cement remaining on the bracket surface (less on the substrate surface).

The results of this study cannot be directly compared to in vivo conditions; however, the results do show an interesting pattern. These finding could prove clinically significant in the following ways:

1. To be able to ensure maximum achievable bond strength of pylon bases if desired.
2. The ability to titrate pylon orientation in order to meet the desired debond strength of each bracket.
3. Titrating pylon orientation to achieve a desired adhesive failure location leaving as much or as little adhesive on the tooth surface as desired.
4. Designing bracket bases to have significantly different shear bond strengths depending on the direction in which the force is applied.

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